

## A Compact Dual Band Polyimide Based Antenna for Wearable and Flexible Telemedicine Devices

Haider K. Raad<sup>1, \*</sup>, Hussain M. Al-Rizzo<sup>2</sup>, Ayman Isaac<sup>2</sup>, and Ali I. Hammoodi<sup>2</sup>

**Abstract**—Recent wearable health monitoring systems use multiple biosensors embedded within a wireless device. In order to reliably transmit the desired vital signs in such systems, a new set of antenna design requirements arise. In this paper, we present a flexible, ultra-low profile, and compact dual band antenna. The proposed design is suitable for wearable and flexible telemedicine systems and wireless body area networks (WBANs). The antenna is inkjet printed on a 50.8  $\mu\text{m}$  Polyimide Kapton substrate and fed by a Coplanar Waveguide (CPW). The proposed design has the merits of compactness, light weight, wide bandwidth, high efficiency, and mechanical stability. The performance of the antenna is also characterized against bending and rolling effects to assess its behaviour in a realistic setup since it is expected to be rolled on curved surfaces when operated. The antenna is shown to exhibit very low susceptibility to performance degradation when tested against bending effects. Good radiation characteristics, reduced fabrication complexity, cost effectiveness, and excellent physical properties suggest that the proposed design is a feasible candidate for the targeted application.

### 1. INTRODUCTION

Recent years have witnessed extensive research activities in the field of flexible and wearable electronics. As of 2012, it has been estimated that there are around 1500 worldwide research groups/centres working on diverse aspects of flexible electronics [1]. Flexible electronics, which can be bent, reconfigured, and rolled, would substantially expand the applications of modern electronic devices.

Their light weight, low energy consumption, manufacturing cost effectiveness, reduced fabrication complexity, in addition to the abundance of inexpensive flexible organic and synthesized films and substrates, make flexible electronics an appealing candidate for the modern electronics market. Moreover, recent developments in miniaturized and flexible energy storage, rollable photo voltaics, and self-powered electronic components have paved the road for such devices to be commercialized [2].

One of the most recent applications of flexible and wearable electronics is in the field of biomedicine. In fact, there has been an exponential utilization of telemedicine systems by health care providers in the past few years due to the increasing demand for remote monitoring of physiological parameters and patients health status. Telemedicine applications include but are not limited to the monitoring of seniors, patients with chronic illnesses and or neurological disorders, and vital signs of astronauts, athletes and firefighters [3]. The health parameters that may be transmitted to remote stations via wireless sensor networks (WSN) range from basal body temperature, heart rate, respiratory rate, blood pressure, to glucose levels (in diabetic patients) and Electro Cardiogram (ECG) signals [4–7]. It is worth noting that in addition to off-body, on-body mode is also essential for communication between sensor devices worn or implanted within the user's body [8].

---

*Received 7 January 2016, Accepted 14 April 2016, Scheduled 29 April 2016*

\* Corresponding author: Haider Khaleel Raad (raad@xavier.edu).

<sup>1</sup> Physics Department, Xavier University, 3800 Victory Pkwy., Cincinnati, OH, USA. <sup>2</sup> System Engineering Department, University of Arkansas at Little Rock, 2801 S. University Ave., Little Rock, AR, USA.



**Figure 1.** Flexible inkjet printed monopole antenna based on a Kapton Polyimide substrate.

To ensure system portability and user convenience, flexible and wearable telemedicine require antennas operating in specific frequency bands to provide wireless connectivity [8].

Obviously, the efficiency of such systems directly depends on the characteristics of the antenna unit on board which is required to be light weight, conformal, ultra-thin, compact, and mechanically robust. At the same time, these antennas should exhibit high efficiency with desirable radiation characteristics.

In current telemedicine systems, different types of biosensors are connected to a low power microcontroller which in turn communicates with the WSN via a radio module. The radio module is usually low-power and is based on one of the short range wireless schemes such as Bluetooth and ZigBee.

On the other hand, Wireless Local Area Network (WLAN) is recognized as the most cost effective and reliable solution for commercial wireless connectivity. It should be noted that the ongoing developments in WLAN technologies require the integration of all IEEE 802.11a/b/g/n standards of the 2.4 GHz (2400–2484 MHz), and 5.2 GHz (5150–5350 MHz) bands into a single antenna unit [9–11].

A plethora of design approaches for flexible and wearable antennas have been reported in the literature in the recent years which are based on different types of substrates/films. Electro textile based radiators seem to be a low profile solution for wearable/conformal applications; however, their substrate materials are more prone to discontinuities [12]. In [13], a flexible inverted-F antenna printed on a paper-based organic substrate was proposed for integration within flexible displays. Although paper based substrates are cost effective, they are found to lack robustness when used in applications that require high levels of flexing and bending. Moreover, they possess a high loss factor which compromises the efficiency of the antenna.

Technically, conventional microstrip antennas are not preferred in flexible electronics since the bandwidth is a function of the substrate's thickness. In [16], a flexible aperture coupled antenna design is reported. This technique significantly enhances the impedance bandwidth, however, it leads to a serious increase in the antenna's profile; furthermore, it involves multi-layer fabrication process.

Previously, the authors of this paper have proposed an Artificial Magnetic Conductor (AMC) antenna based on Kapton Polyimide. The design was intended for integration within flexible telemedicine systems [17]. The main feature of the design was its reduced Specific Absorption Rate (SAR) which is essential to minimize the potentially harmful exposure to electromagnetic waves in applications that require moderate to high power. Polyimide and vinyl were chosen as the antenna's substrates. Kapton was identified as the main antenna deposition platform due to its good balance of physical, chemical, and electrical properties in addition to its low loss factor over a wide frequency range ( $\tan \delta$  is 0.002 at 2.45 GHz). Furthermore, Kapton Polyimide is available at a very low thickness (50.8  $\mu\text{m}$ ), yet, very robust with a tensile strength of 165 MPa at 73°F (compared to 17 MPa for paper-based substrates), a dielectric strength of 3500–7000 volts/mil, and a temperature rating of  $-65$  to  $150^\circ\text{C}$  [18]. However, the antenna proposed in [17] involves multiple layers and as mentioned above is suitable for moderate to high power applications. Moreover, the antenna is not suitable for integration within compact devices due to its relatively large dimensions.

In this paper, we propose a Co-Planar Waveguide (CPW) fed dual band antenna inkjet printed on a 50.8  $\mu\text{m}$  Kapton Polyimide substrate. In addition to its ultra-low profile, compactness, and flexibility, the design is more feasible than the above-mentioned feeding techniques since it offers several advantageous characteristics such as: reduced radiation losses, improved impedance matching and bandwidth, and more importantly, low fabrication cost and complexity since both radiating element and ground plane

are deposited on the same side of the substrate, which promotes roll to roll production and a consistent thickness throughout the topology.

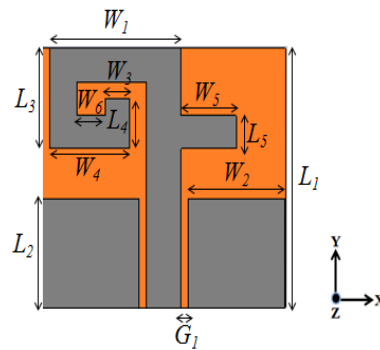
In Section 2, the design of the proposed flexible dual band antenna is presented. In Section 3, detailed description of the fabrication process of the proposed design is discussed. The electromagnetic performance, radiation characteristics of the proposed design are presented in Section 4. Flexibility analysis is reported in Section 5. Finally, conclusions are given in Section 6.

## 2. ANTENNA DESIGN

Planar monopole and dipole antennas have received more attention over other antenna types especially in wearable and flexible applications. For WLAN technologies, printed monopole antennas are preferred over other topologies due to their relatively large impedance bandwidth, low profile, fabrication simplicity, and omni-directional radiation pattern which is highly desired in WLAN systems.

As shown in Fig. 2, the antenna consists of a winding branched radiating element fed by a CPW. This miniaturization technique lengthens the current path which consequently reduces the structure size without significant degradation to the radiation characteristic of the antenna. The antenna structure is printed on a 31 mm 34 mm Kapton Polyimide substrate with a dielectric constant of 3.4 and a loss tangent of 0.002. To feed the radiating element, a CPW transmission line which consists of a central strip with a width of 4 mm and a 1 mm gap between the central strip and the coplanar ground plane is used.

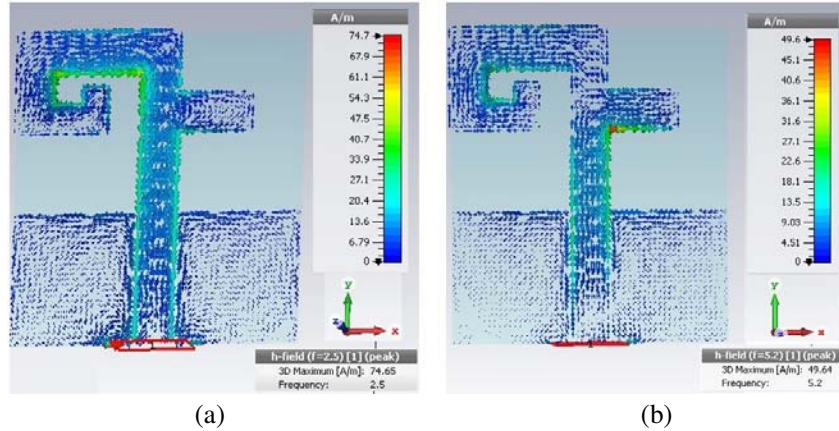
The foundation of the antenna structure is technically based on a rectangular patch monopole which is centred asymmetrically at the end of the CPW central strip line. To achieve the desired dual-band behaviour, U-shaped slits which comprise both horizontal and vertical sections are introduced (subtracted from the patch). The introduction of these slits is to produce two distinct current paths and thus dual resonant modes are excited. Obviously, the longer arm gives rise to the lower resonance while the short arm is responsible for the upper resonance. This is also evident from the simulated surface current distribution graphs depicted in Fig. 3. It is also worth mentioning that a parametric



**Figure 2.** Geometry and dimensions of the proposed dual band printed monopole antenna (the grey coloured area represents the metallization of ground plane and the radiating element).

**Table 1.** Dual band printed monopole antenna (dimensions in millimetre).

<b>L1</b>	31	<b>W2</b>	14
<b>L2</b>	13	<b>W3</b>	3.5
<b>L3</b>	12	<b>W4</b>	11.5
<b>L4</b>	6	<b>W5</b>	8
<b>L5</b>	4	<b>W6</b>	4
<b>W1</b>	19	<b>G1</b>	1



**Figure 3.** Surface current distributions of the proposed antenna at (a) 2.5 GHz, and (b) 5.2 GHz.

study was conducted to investigate the gaps and ground plane size effects on the resonant frequencies and return loss of the antenna. As mentioned previously, the branched radiating element is fed by a CPW feed reduces the fabrication complexity as both the radiating element and ground plane are deposited on the same side of the substrate. The geometry and dimensions of the antenna are depicted in Fig. 2 and Table 1.

### 3. FABRICATION PROCESS

The final optimized design is fabricated by inkjetting a conductive ink based on silver nano-particles by a material printer followed by a thermal annealing process which is necessary for the solvent evaporation.

A Dimatix DMP 2800 ink-jet printer is utilized to deposit the CPW fed antenna along with the ground plane using a piezo ink-jet cartridge which contains 16 nozzles with a diameter of 23  $\mu\text{m}$  with a default drop size of 10 pico litre.

The Dimatix material printer is equipped with a 200 mm  $\times$  300 mm printing surface with a controllable vacuum platen and integrated with a fiducial camera [19].

For solvent evaporation, the platen should be preheated appropriately (below the melting point of the substrate/film) prior to placement of the substrate. For Kapton Polyimide, 60 is selected. The spacing between the substrate and the tip of the nozzle should also be adjusted according to the thickness of the substrate and is preferably adjusted slightly more than the substrate's thickness (between 100 to 150  $\mu\text{m}$ ). It should be noted that depositing one layer of ink on the substrate would sometimes leads to pattern inconsistency. In our case, three layers of silver nano particle based ink are deposited on the substrate and is found to be optimal to achieve a robust and continuous radiating element.

Finally, the printed metallic patterns need to be thermally annealed to evaporate the solvent combined with the silver particles mixture in order to achieve the highest electric conductivity which directly enhances the antenna's efficiency. Moreover, thermal annealing is essential to prevent pattern oxidization which also compromises the electric conductivity of the radiating element.

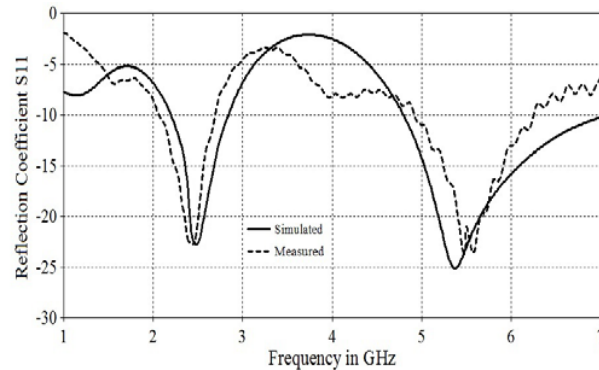
The thermal annealing process is conducted utilizing the ProtoFlow LPKF's which is an industrial high-precision convection oven. The annealing temperature is set to 110 while the heating duration is fixed at 4 hours which was found to be optimal.

### 4. MEASUREMENTS

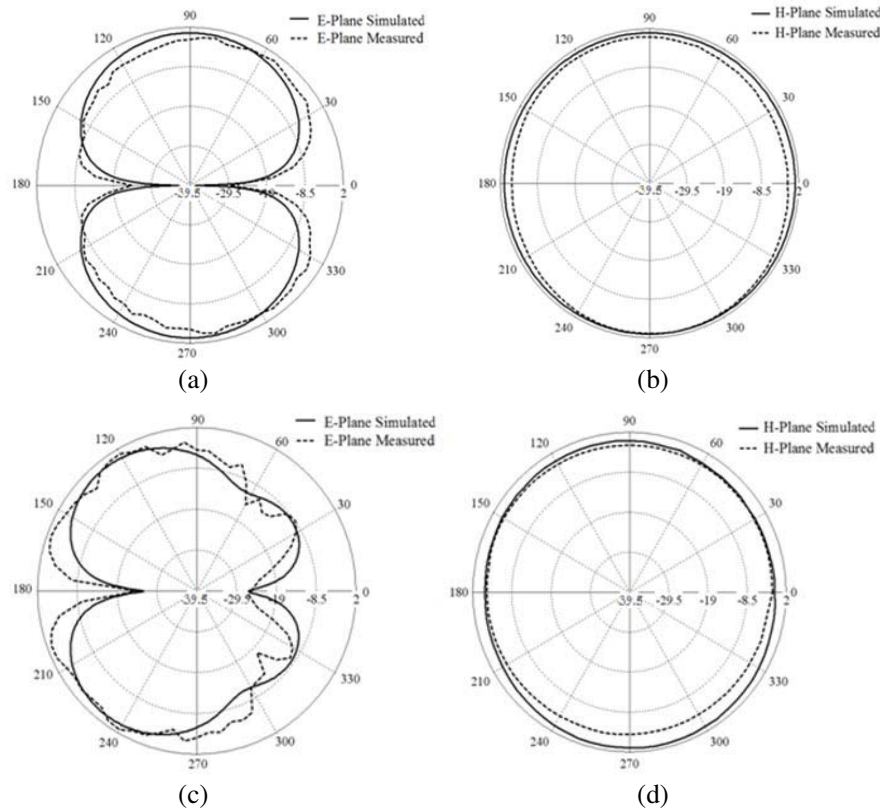
Design and analysis of the proposed printed monopole antenna have been carried out using the full wave simulation package CST Microwave Studio which is based on the Finite Integration Technique (FIT). CST offers accurate, efficient computational solutions for RF and electromagnetic design and analysis with different computational solvers. In this paper, all simulations have been conducted using the time-domain solver [20].

The antenna’s S-parameters were measured using an Agilent PNA-X series N5242A Vector Network Analyser (VNA) with (10 MHz–26.5 GHz) frequency range.

As can be seen in Fig. 4, a good agreement is achieved between the simulated and measured reflection coefficient  $S_{11}$  except for a slight shift in the second resonance. The simulated return loss for the antenna is 22.8 dB at 2.5 GHz, with a  $-10$  dB bandwidth of 662 MHz (27%), while the measured return loss is 22.4 dB at 2.46 GHz with a  $-10$  dB bandwidth of 648 MHz (also 27%). On the other hand, the simulated return loss is 25 dB at 5.35 GHz with a bandwidth of 2125 MHz (40%), and the measured return loss is 23.7 dB at 5.48 GHz with a 1378 MHz (26%). The observed difference in the upper resonance bandwidth results is attributed to the open boundary condition definition which was set up



**Figure 4.** Measured and simulated reflection coefficient  $S_{11}$  for the dual band printed monopole.



**Figure 5.** Measured and simulated  $E$ -plane ( $YZ$ ) and  $H$ -plane ( $XZ$ ) radiation patterns for the dual band printed monopole at 2.45 GHz ((a) and (b)); and at 5.35 GHz ((c) and (d)).

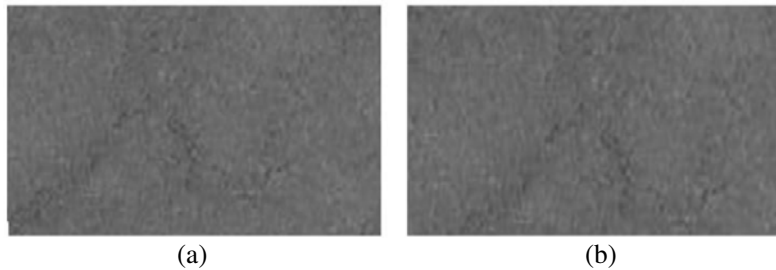
at the lowest resonance (2.45 GHz), in addition to the non-realistic wave port excitation assumed in the simulation process. However, the proposed antenna sufficiently covers the targeted frequencies and the required operational bandwidth. It is worth mentioning that the electrical conductivity of the silver nano particle based ink has been measured using the traditional four-probe method and was found to be  $8.9 \times 10^5$  S/m. This reduced conductivity caused by the solvent and impurities decreases the quality factor which explains the relatively enlarged impedance bandwidth of the proposed antenna. The simulated efficiency of the antenna is 91.6%.

The far-field radiation patterns of the principal planes ( $E$  and  $H$ ) were measured in the University of Arkansas at Little Rock's anechoic chamber. The Antenna Under Test (AUT) was placed on an ETS Lindgren 2090 positioner and aligned to a horn antenna with adjustable polarization.  $E$ -plane ( $YZ$  cut) and  $H$ -plane ( $XZ$  cut) far-field radiation patterns for the resonances under consideration are depicted in Fig. 5. It can be seen that the radiation power is omni-directional at both resonant frequencies. The antenna achieved measured gains of 1.68 dBi and 1.64 dBi at 2.45 GHz and 5.35 GHz, respectively, which fairly agree with the simulated values.

## 5. FLEXIBILITY ANALYSIS AND COMPARATIVE STUDY

During a realistic operation, the antenna is expected to be flexed, bent, and/or rolled. Hence, two tests need to be conducted to characterize their electromagnetic and mechanical performance during operation [21].

To ensure mechanical durability and consistent functionality, qualitative tests are required. This is done by applying repeated bending, curving and twisting to the antenna and check for any deformations and discontinuities in the radiating element via visual and/or microscopic inspection if necessary. On the other hand, the electromagnetic performance of the antenna, namely, the return loss and resonant frequency are required to be evaluated through testing against bending effects. As stated previously, Polyimide Kapton substrate was chosen as the antenna's substrate due to its desirable physical properties such as mechanical robustness, high tensile strength, thermal stability, low loss tangent, and high flexibility. When the prototype was tested repetitively (over a hundred times) under bending and curving effects, no significant wrinkles or cracks have been observed even at the microscopic level as shown in Fig. 6.

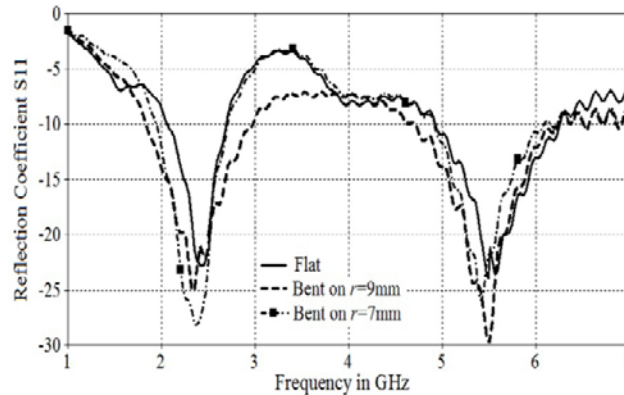


**Figure 6.** SEM layout of the thermally annealed deposited pattern before flexing and bending (a), and after (b).

For the second test, the antenna is conformed and affixed by an adhesive tape on foam cylinders (having different radii (the first is  $r = 9$  mm while the second is  $r = 7$  mm) which are utilized to emulate different bending extents while it is connected to the network analyser.

As can be seen in Fig. 7, a slight shift to a lower frequency at both resonances of the dual band antenna is experienced when it is conformed on a 9 mm and 7 mm radii foam cylinders which emulate two different bending extents. However, the relatively large impedance bandwidth of the AUT overcomes the encountered shift caused by the bending effect. It is worth noting that the wear and tear of such antennas largely depend on the targeted application. For example, the antenna would be less susceptible to bending if it is integrated within clothing or conformed on a rigid curved object as compared to integrating the antenna within a small foldable handheld device. In telemedicine applications, such



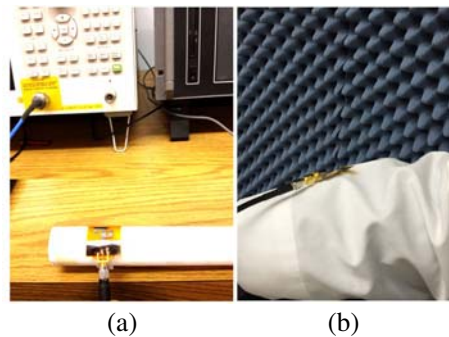


**Figure 7.** Measured  $S_{11}$  for the proposed dual band antenna when bent on foam cylinders with different radii ( $r = 9$  mm and  $r = 7$  mm) to mimic different bending extents.

antennas would be mainly integrated within clothing (smart medical hospital gowns), or vital signs bracelets and patches which generally do not require continuous folding and bending.

In addition to the foam cylinder measurements, the antenna has been tested when operated close to the user's tissues which reflects a practical scenario. The antenna was affixed, while connected to a network analyser, on a subject's arm wearing one layer of light clothing in the first setup and two layers in the second setup. Slight shift in the resonant frequency and return loss was observed in the first setup (around 18 MHz at 2.45 GHz, and 45 MHz at 5.2 GHz). However, the relatively large impedance bandwidth could compensate for the encountered shift which does not affect the operation of the antenna.

Figure 8 depicts the flexibility test setup for the proposed dual band antenna conformed on a foam cylinder with on 9 mm radius, and on a live subject's arm.



**Figure 8.** Flexibility test setup (AUT is conformed over a cylindrical foam with different radii to reflect different extents of bending) (a), and affixed on a subject's arm (b).

The antenna proposed in this paper was compared to different types of flexible antennas reported in the literature [12–15]. Given the application targeted in this paper, the comparative study is focused on compactness (size and thickness), electrical and mechanical properties such as tensile strength, thermal stability, flexural strength, and deformability. Fabrication complexity is also considered in this comparative study. Furthermore, to ensure a consistent performance of the antenna when operated under higher temperatures (than ambient temperature), a simple thermal analysis has been conducted. The proposed antenna was exposed to a heat gun with a controlled temperature by a digital thermometer while connected to a network analyser (temperature was varied from 15 to 100 Celsius). Due to the high thermal endurance of the Polyimide kapton substrate, and the thermal stability of the annealed silver nanoparticle based ink, no change was reported in the resonant frequency or the return loss of the proposed antenna. Properties under comparison are reported in Table 2.

**Table 2.** Comparison of different types of flexible antennas.

Characteristics	Proposed dual band antenna	Textile antenna [12]	Paper based antenna [13]	Fluidic antenna [14]	Flexible Bow-tie antenna [15]
Size mm	31 x 34	180 x 150	46 x 35	54 x 10	39 x 25
Thickness mm	0.05	4	0.25	1	0.13
Band/ $f_0$	Dual/2.5, 5.2 GHz	Dual/2.2, 3 GHz	Single/2.4 GHz	Single/1.85 GHz	Single/7.6 GHz
Substrate	Polyimide $\epsilon_r=3.4$	Felt fabric $\epsilon_r=1.5$	Paper $\epsilon_r= 3.4$	PDMS $\epsilon_r= 2.67$	PEN film $\epsilon_r=3.2$
Dielectric loss	Low loss $\tan \delta=0.002$	High loss $\tan \delta=0.02$	High loss $\tan \delta=0.065$	High loss $\tan \delta=0.37$	Low loss $\tan \delta=0.015$
Tensile strength	High (165 MPA)	Low (2.7 MPA)	Low (30 MPA)	Low (3.9 MPA)	High (74 MPA)
Flexural strength	High (50000 p.s.i)	Low (8900 p.s.i)	Low (7200 p.s.i)	Low (650 p.s.i)	High (13640 p.s.i)
Deformability	Low	High	High	High	Low
Thermal stability	High	Low	Low	Low	High
Fabrication complexity	Simple/Printable	Complex/Non-printable	Simple/Printable	Complex/Non-printable	Simple/Printable

## 6. CONCLUSION

In this paper, the design, fabrication, and testing of flexible and compact printed dual band antenna are discussed in details. The reported design is based on a Kapton Polyimide substrate which is known for its flexibility, mechanical robustness and low dielectric losses. Moreover, the antenna is tested under bending conditions experimentally since it is expected to be flexed and/or conformed on curved surfaces during operation. It is shown that the proposed antenna exhibits a minor shift and degradation in the return loss and resonant frequencies under consideration when the extent of bending is increased. Ultra flexibility, compactness, mechanical robustness, reduced fabrication complexity along with excellent radiation characteristics and efficiency suggest that the reported design is a feasible candidate for integration within flexible and wearable telemedicine devices.

## REFERENCES

1. Ko, H., R. Kapadia, K. Takei, T. Takahashi, X. Zhang, and A. Javey, "Multifunctional, flexible electronic systems based on engineered nanostructured materials," *Nanotechnology*, Vol. 23, No. 34, 11, 2012.
2. Huang, Y., J. Chen, Z. Yin, and Y. Xiong, "Roll-to-roll processing of flexible heterogeneous electronics with low interfacial residual stress," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 1, No. 9, 1368–1377, Sept. 2011.
3. Vanveerdeghem, P., P. Van Torre, C. Stevens, J. Knockaert, and H. Rogier, "Flexible dual-diversity wearable wireless node integrated on a dual-polarised textile patch antenna," *IET Science, Measurement & Technology*, Vol. 8, No. 6, 452–458, Nov. 2014.
4. Bahrami, H., S. A. Mirbozorgi, R. Ameli, L. A. Rusch, and B. Gosselin, "Flexible, polarization-diverse UWB antennas for implantable neural recording systems," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 10, No. 1, 38–48, Feb. 2016.
5. Khaleel, H. R., H. Al-Rizzo, D. Rucker, and Y. Al-Naiemy, "Flexible printed monopole antennas for WLAN applications," *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 1334–1337, Jul. 3–8, 2011.



6. Bahramiabarghouei, H., E. Porter, A. Santorelli, B. Gosselin, M. Popović, and L. A. Rusch, "Flexible 16 antenna array for microwave breast cancer detection," *IEEE Transactions on Biomedical Engineering*, Vol. 62, No. 10, 2516–2525, Oct. 2015.
7. Huang, H., "Flexible wireless antenna sensor: A review," *IEEE Sensors Journal*, Vol. 13, No. 10, 3865–3872, Oct. 2013.
8. Ouyang, Y., D. Love, and W. Chapel, "Body-worn distributed MIMO system," *IEEE Trans. on Vehicular Tech.*, Vol. 58, No. 4, 16–22, May 2009.
9. Sanz-Izquierdo, B., J. A. Miller, J. C. Batchelor, and M. I. Sobhy, "Dual-band wearable metallic button antennas and transmission in body area networks," *IET Microwaves, Antennas & Propagation*, Vol. 4, No. 2, 182–190, Feb. 2010.
10. Chen, H.-D., J.-S. Chen, and Y.-T. Cheng, "Modified inverted-L monopole antenna for 2.4/5 GHz dual-band operations," *IEE Electron. Lett.*, Vol. 39, No. 22, 1567–1568, Oct. 2003.
11. Wu, J. W., H. M. Hsiao, J. H. Lu, and S. H. Chang, "Dual broadband design of rectangular slot antenna for 2.4 and 5 GHz wireless," *IEE Electron. Lett.*, Vol. 40, No. 23, 1461–1463, Nov. 2004.
12. Salonen, P., J. Kim, and Y. Rahmat-Samii, "Dual-band E-shaped patch wearable textile antenna," *IEEE Antennas and Propagation Society Symposium*, Vol. 1, 466–469, 2014.
13. Anagnostou, D., A. Gheethan, A. Amert, and K. Whites, "A direct-write printed antenna on paper-based organic substrate for flexible displays and WLAN applications," *Journal of Display Technology*, Vol. 6, No. 11, 558–564, Nov. 2010.
14. So, J., J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, and M. D. Dickey, "Reversibly deformable and mechanically tunable fluidic antennas," *Advanced Functional Materials*, Vol. 19, No. 22, 3632–3637, Oct. 2009.
15. Durgun, A. C., M. S. Reese, C. A. Balanis, C. R. Birtcher, D. R. Allee, and S. Venugopal, "Flexible bow-tie antennas," *Antennas and Propagation Society International Symposium (APSURSI), IEEE*, 1, Jul. 2010.
16. Hertleer, C., A. Tronquo, H. Rogier, L. Vallozzi, and L. Van Langenhove, "Aperture-coupled patch antenna for integration into wearable textile systems," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 392–395, 2007.
17. Raad, H., A. Abbosh, H. Al-Rizzo, and D. Rucker, "Flexible and compact AMC based antenna for telemedicine applications," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 2, 524–531, Feb. 2013.
18. Dupont Kapton Polyimide specification sheet, [www2.dupont.com/kapton](http://www2.dupont.com/kapton).
19. [http://www.fujifilmusa.com/products/industrial\\_inkjet\\_print\\_heads/index.html](http://www.fujifilmusa.com/products/industrial_inkjet_print_heads/index.html).
20. <http://www.cst.com>.
21. Khaleel, H. R., H. Al-Rizzo, and D. Rucker, "Compact polyimide-based antennas for flexible displays," *Journal of IEEE Display Technology*, Vol. 8, No. 2, 91–97, Feb. 2012.